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SATELLITE POSITIONING FOR GEOSCIENCES

The space geodesy revolution for plate tectonics and earthquake studies

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Abstract Even if plate tectonics was a truly significant unifying theory that began to give sense to a series of different geological observations, plate motions were considered scattered. The advent of space geodesy confirmed and greatly refined the models of plate kinematics, allowing also to study the motion of the lithosphere with respect to the inner layers of the Earth. Switching from the no net rotation to the hotspot reference frames, plate motion assumes coherence with a mean global westward drift of the lithosphere with respect to the mantle. However, the driving forces of plate tectonics are still under investigation and space geodesy may provide fundamental tools to develop comprehensive models which can take into account the contributes of mantle density gradients and astronomical forces, as Earth's rotation and tides. This paper is dedicated to Prof. Michele Caputo who was a pioneer in measuring the misalignment of the tidal bulge with respect to the Earth–Moon gravitational alignment. The misplaced mass in excess may account for the westerly directed torque of the lithosphere relative to the mantle. Local GPS networks and satellite observations are providing new insights on plate boundary tectonics and allow unravelling the evolution of the interplay between the shallow brittle upper crust and the underlying visco-plastic lower crust, which is deforming in a steady state regime without releasing relevant seismic waves. Along active tectonic areas, zones marked by low strain rates are suitable to store larger energy, subsequently dissipated during the coseismic stage. GPS and InSAR observations have widely increased the capability to monitor the spatial and temporal variations of deformation. The coseismic deformation pattern suggests a different mechanism of energy store and release, mainly gravitational in extensional tectonic settings and essentially elastic in strike-slip and contractional tectonic settings. The increasing details provided by future dense and low-cost geodetic networks will allow to detect reliable deformation transients and new insight on seismic precursors.

Keywords Space geodesy · Plate motion · Seismic cycle · Strain rate

1 Introduction

Since the discovery of plate tectonics, the data provided by space geodesy have probably been the major breakthrough in terms of new data and interpretation. Among current challenges of geosciences, the driving mechanisms of plate tectonics still represent a major topic in which space geodesy is providing fundamental data (Gordon and Stein 1992). Geodesy uses a wide range of Earth's observation systems and space technologies contributing to our understanding of geodynamics and the Earth interactions with other planetary bodies (Mueller and Zerbini 1989; Barzaghi et al. 2015). Our society limits in the face of natural disaster occurrence remind us that the Earth is a rather complicated system, which requires modern and sophisticated techniques to detect the variations due to the Earth dynamics and global

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change. The large amount of data now at disposal by space geodesy permits more refined models, which increase our predictive capabilities of natural disasters (Bilham and Zerbini 1989). The classical pillars of Geodesy (Earth's gravity field, rotation/polar motion and geometry of the surface) are today as in the past but with increased accuracy, reliability and availability through International Services, the modern basis on which current geodynamic studies are carried on at different scales, from the global plate motion to the fault level (Jin et al. 2013).

2 Global plate motion

Since about 1960 we know, thanks to space geodesy (VLBI, SLR and more recently GNSS), the motion direction and velocity of the major plates of the Earth's lithosphere in a no net rotation frame (NNR) defined by the International Earth Rotation and Reference Systems Service (ITRF, e.g., Altamimi et al. 2012). The NNR hypothesis is the arbitrary choice introduced to fix the rank deficiency proper of the positions estimation problem based on space geodetic observations. Surface data are able to describe only relative plate motions, whereas any absolute motion with respect to the mantle cannot be accounted for.

It has been shown that motions from space geodetic data (ITRF) correlate quite well with the motions predicted by the Nuvel models. The Nuvel models are defined in a no net rotation frame since based on relative observations like past ocean floor magnetic anomalies and earthquake focal mechanisms (DeMets et al. 2010 and reference therein). The coherence between the current geodetic and the Nuvel models has evidenced a good match between the past and present day plate motions (Stein 1993), thus inferring that the current plate motion models are a good indicator of the main Cenozoic and Neozoic plate movements. Therefore, the present day plate motion is comparable to those expected to have occurred in the past million years.

On the other hand, it is worth noting that the global analysis of tectonic features such as transform faults, subduction zones, and rifts can also contribute to the present and past plate motion descriptions. Using the major tectonic features on Earth, the plates appear not moving randomly, but they rather follow an undulated sinusoidal flow (Doglioni 1990, 1993), with possible second-order sub-rotations (Cuffaro et al. 2008). Moreover, plate motions appear westerly polarized when represented with respect to the mantle: the so-called net rotation or "westward drift" of the lithosphere (Bostrom 1971; Ricard et al. 1991; O'Connell et al. 1991) can be evidenced both with respect to the Antarctica plate (Le Pichon 1968; Knopoff and Leeds 1972) as well as to the hotspot reference frame (HSRF) (Gordon 1995; Henderson 2001; Gripp and Gordon 2002; Crespi et al. 2007). The existence of a westward drift polarizing the sinusoidal flow is supported by independent geological and geophysical evidences, such as the asymmetry of subduction and rift zones following or opposing the relative counter motion of the mantle (e.g., Doglioni et al. 2003; Doglioni and Panza 2015).

In principle, the definition of any plate kinematic model with respect to the mantle should be based on an optimal choice of the hotspot candidates to realize a suitable reference frame. The plate on which the selected hotspots are located becomes the reference plate defining the known tangential velocity with respect to the mantle and any potential depth assigned to the hotspot source reflects directly on the velocity assumed by the reference plate with respect of the mantle (Fig. 1). This is a crucial point in HSRF definition, which can lead to debate and criticisms at least until the knowledge of the relative motions between the different layers of Earth will increase in the future.

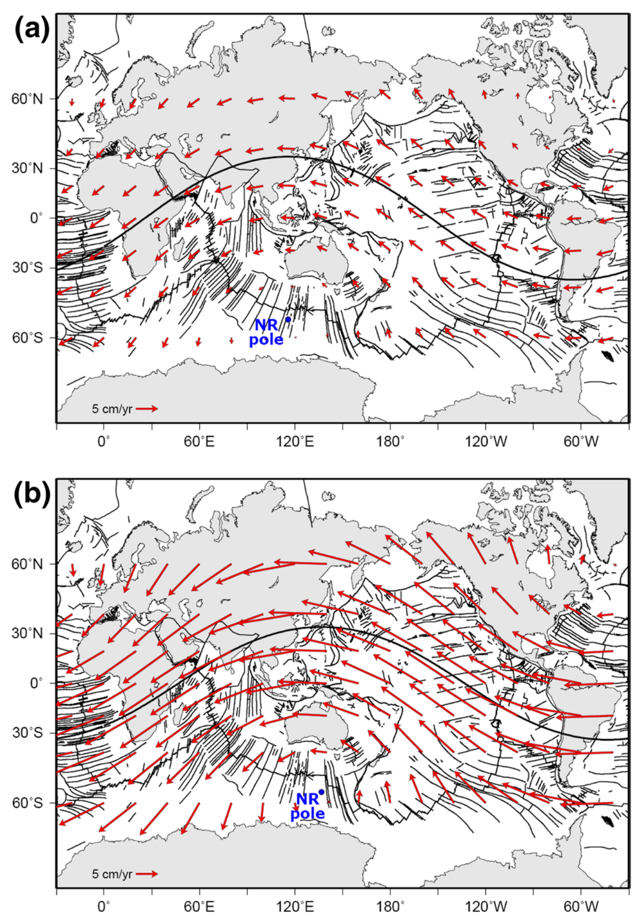

Fig. 1 Net rotation of the lithosphere with respect to **a** deep and **b** shallow HSRF, according to the model by Crespi et al.(2007). *Red arrows* are the model velocities computed over regular grid. The *black line* is the net rotation equator, i.e., the line of maximum tangential velocity. The *blue bullet* indicates the net rotation pole (colour figure online)

The choice of deep rooted HSRF leads as consequence to a minimum mean lithospheric rotation which is not a global phenomenon, where all the plates have a polarized westward motion with different relative velocities; this choice has been so far preferred (e.g., Ricard et al. 1991), because it preserves the angular momentum of the Earth without rapidly decelerating its rotation speed.

However, models of a global lithospheric rotation are physically feasible if there is a transition zone with different rheologies which decouples the lithosphere from the asthenosphere. There are growing evidences of a low velocity layer in the upper asthenosphere (Rychert and Shearer 2009; Rychert et al. 2013), which can be associated with a water-rich and low-viscosity upper mantle, where decoupling can focus (Riguzzi et al. 2010).

Following this conjecture, a global rotation of the lithosphere would occur under the action of long wavelengths (Scoppola et al. 2006; Riguzzi et al. 2010; Doglioni et al. 2011a) of astronomical origin and the combination of rotation under tidal torque, efficient internal convection, and lateral viscosity variations at the lithosphere–mantle interface where are supposed to exist thin hydrate layers with very low viscosity. Mantle convection appears polarized, since lithospheric recycling is faster along W-directed subduction zones (Doglioni and Anderson 2015). Moreover, the tidal bulge is misaligned relative to the gravitational alignment between Earth and Moon (Caputo 1985), thus providing a westerly directed torque acting on the lithosphere. Therefore, mantle convection, tidal drag, and Earth's rotation concur in propelling and tuning plate tectonics in a sort of self-organized chaotic system (Doglioni et al. 2007). The Gutenberg–Richter earthquake frequency versus magnitude distribution all over the Earth is a statistical evidence that the engine of plate tectonics is acting contemporaneously at global scale. The horizontal component of the solid Earth's tide seems a reliable candidate able to provide the energy to move horizontally the lithosphere, with locally variable velocity controlled by the viscosity values at the lithosphere base within the low-velocity layer at the top of the asthenosphere, between 100 and 200 km depth.

A comprehensive dynamic model of the solid Earth could surely be a future challenge for geodesy and geodynamics together.

3 Fault scale

Geological and geodetic observations are useful to model the so-called seismic cycle, i.e., the deformation history of a fault. A seismogenic fault is a crust discontinuity immersed in a slowly varying deformation field, mainly sustained by the lithospheric plate motion with respect to asthenosphere and transferred to the Earth's surface by the coupling/uncoupling through the brittle ductile transition zone (BDT) (Doglioni et al. 2011b). Geodetic techniques measure the surface displacements within the earthquake cycle, but due to the viscoelastic behaviour of the lower crust and mantle lithosphere, the surface deformations vary throughout the seismic cycle.

One limitation to study the seismic cycle is surely represented by the limited time span of geodetic observations. In fact, the deformation field appears to be stationary if measured faraway from earthquakes, since current accuracy cannot account for very low rates. However, we can measure and model that early in the cycle (close to the earthquake occurrence), viscous flow in the lower crust exerts a traction on the upper crust and produces high velocity gradients across active faults, i.e., high strain rates (e.g., Devoti et al. 2012). The opposite occurs late in the cycle, where the strain rate decreases very slowly across faults (Riguzzi et al. 2012). Variations in the strain rate may also be related to lithological variations that control the internal friction within the crust and the upper mantle. The cycle appears to develop faster in extensional environment and much more slow in compressional regimes; in fact, the relaxation time of thrust faults (contractional) has been evaluated three times larger than the relaxation time of normal faults (extensional) (Riguzzi et al. 2013).

Geodetic observations are then the primary source of information able to record the coseismic and interseismic crustal deformation consequent to rupture and locking stage of faults.

Currently, the coseismic stage of a fault and the consequent permanent deformations are rather well studied (e.g., Segall 2010). The source models are usually based on a theory of fault dislocation in an elastic half-space (i.e., dislocation theory, e.g., Savage 1983); however, we still lack the details about the rupture style, the role of gravity in extensional environment which seems to be the largest contribute to move normal faults (Doglioni et al. 2015), the effect of listric geometries or secondary splay faults, and the inelastic behaviour of the lithosphere if ripe or incipient faults act differently and interact with each other.

The geodynamics of the Apennines is controlled by the 'easterly' subduction retreat of the Adriatic-Ionian slab. This mechanism provides contractional tectonics in the frontal thin-skinned accretionary prism and contemporaneous thick-skinned backarc extension along the Apennines and Tyrrhenian Sea. Local transfer zones of differential slab retreat, salients, and recesses in the accretionary prism and transfer zones within the dilatational backarc basin are rather characterized by strike-slip tectonics. This scenario is shaped by different geotherms that generate variable depth of the BDT, hence controlling the volumes that can be activated during the seismic cycles. The largest extensional earthquakes occur where the BDT is deeper along the Apennines

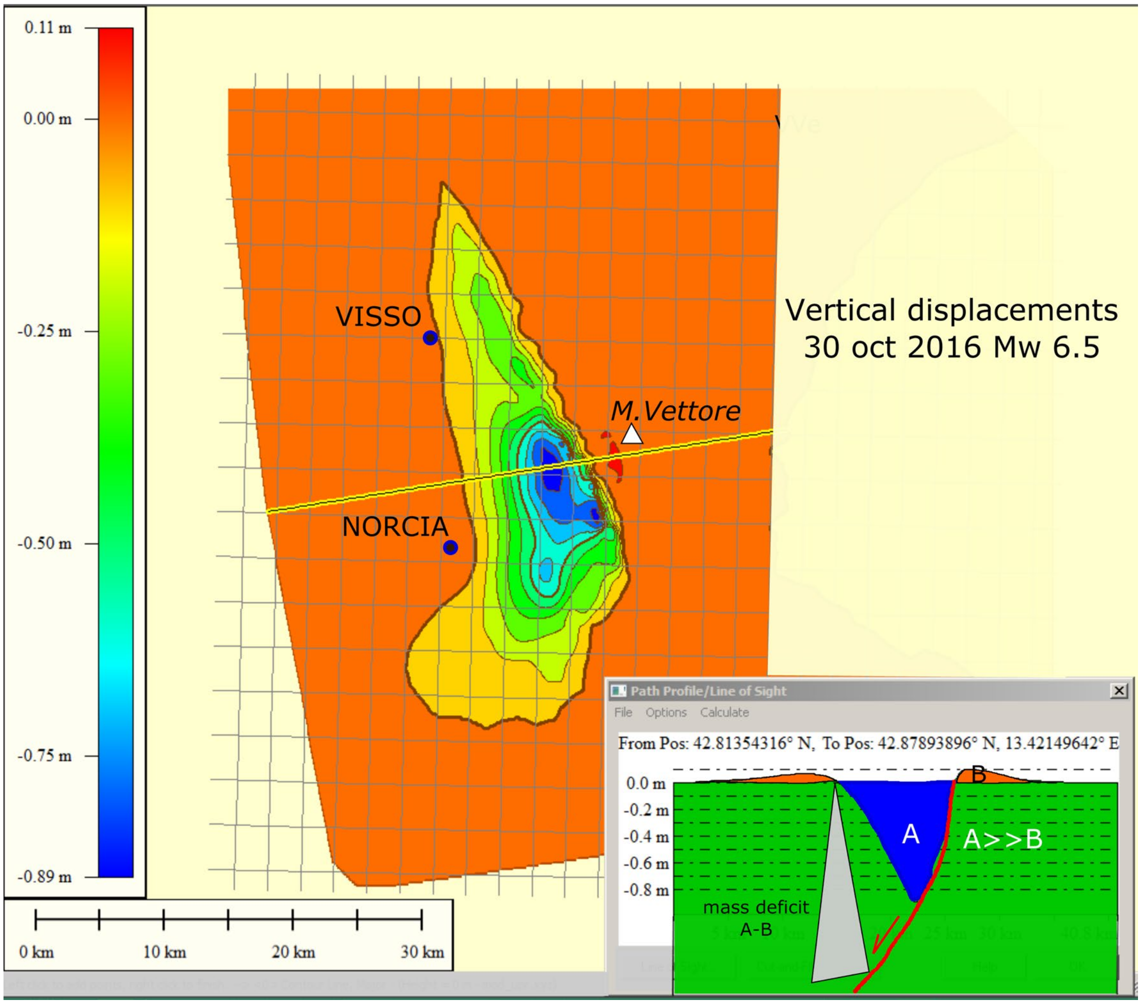

Fig. 2 Map of the cumulative vertical displacements modeled from InSAR data after the 30 October 2016 Mw 6.5 earthquake. The data have been interpolated over a regular grid by GlobalMapper©. The displacements projected along the profile show that in a simple way, the subsided area (A, *in blue*) is larger than the uplifted (B, *in orange*), evidencing that extensional earthquakes account for closure at depth of dilated micro-fractures created in a volume of the brittle upper crust during the interseismic stage. The displacement range is from subsidence of −0.89 m to uplift of 0.11 m. The profile is in scale, while the fault and the mass deficit triangle are only an indicative cartoon (displacement data courtesy of Simone Atzori, INGV) (colour figure online)

belt. This happens where the topography is higher and the lithostatic load (σ_1) is therefore greater, increasing the differential stress. Vice versa, the most energetic contractional earthquakes generate where the topography is low, since the lower the lithostatic load (σ_3), the larger the differential stress. All earthquakes are associated with the propagation of elastic waves. However, they are activated by different types of energy. In contractional and strike-slip settings, the earthquake dissipates mainly the elastic energy accumulated within a volume above the creeping layer of the crust. In extensional settings, the earthquakes seem evidence of gravitational collapse of brittle upper crustal prisms. Since the evolution and energy accumulation of earthquake preparation and nucleation between normal fault and thrust-related earthquakes are different, we believe useful to distinguish the different processes, i.e., graviquakes and elastoquakes. In extensional setting, the maximum depth of the seismogenic zone is about one-third with respect to the length of the volume affected by the collapse (Petricca et al. 2015). The dimension of the volume constrains the length of the fault system that allows the crustal volume to collapse and deform into a sag basin. InSAR data of the 2016 Amatrice-Norcia sequence (Cheloni et al. 2017) show that the subsided area during the coseismic stage is larger than the uplifted area, thus evidencing that extensional earthquakes are due to the closure at depth of dilated micro-fractures created in a volume of the brittle upper crust during the interseismic stage (Fig. 2). The stored and released gravitational energy is large and dissipated by the earthquake together with elastic energy, folding, fracturing, and shearing rocks, confirming

its significant role in the seismic event dynamics. This may also explain why aftershocks last longer along normal faults, since the crust will continue to move because favoured by the gravity, until the equilibrium will be reached; on the contrary, along thrusts, the aftershocks are inhibited, because the volume should move against gravity.

Seismic precursors, if any, may then have different signs and this can be one of the reasons why they have not yet been recognized.

Therefore, an interesting number of open questions and unsolved issues ask for future challenges toward a large spatial and temporal increase of geodetic data, through the developmentof dense and low-cost geodetic network (e.g., Hung et al. 2017), will permit more sophisticated models and increasing predictive capabilities of natural disasters such as earthquakes.

Acknowledgements We are delighted to have contributed to the meeting and the volume in honour of Professor Michele Caputo. We want to recall here his outstanding scientific stature, the endless number of milestone contributions in a variety of different scientific fields, spanning from seismology, geodesy, mathematics, astronomy, etc. Several generations of scientists have learned a lot from him and are perpetually grateful. We wish also to warmly thank the Editors and two anonymous reviewers.

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